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The Construction and Calibration of a Standard Air Condenser

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THE CONSTRUCTION AND CALIBRATION OF A STANDARD AIR CONDENSER

BY

WILLIAM HARRY BAIR

B. S. Ohio Northern University, 1908

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN PHYSICS

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1914

1914
B16

UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

June 6 1914

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

WILLIAM HARRY BAIR

ENTITLED THE CONSTRUCTION AND CALIBRATION OF A STANDARD AIR CONDENSER

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE IN PHYSICS

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Committee
on
Final Examination

284531

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C O N T E N T S

		Page
I	Introduction	1
II	Historical	1
III	Construction of the Condenser	6
IV	Measurement of Capacity - Absolute Method	9
V	Measurement of Capacity - Comparison Method	15
VI	Data and Results	17

I INTRODUCTION

The accurate measurement of capacities, especially those of small values, has always been an important problem. With the introduction of wireless telegraphy, in which capacities play an important part, the problem of capacity measurements has increased in importance until at the present time the absence of a good standard of capacity or good methods of measuring capacity, leaves a wide gap in the equipment of any research laboratory. The conditions which any good method of measurement must fulfil are accuracy, convenience and rapidity. Of the two general methods of measurement, the absolute and the comparison, the former usually presents more practical difficulties than the latter. In fact there are several very satisfactory and convenient comparison methods of measuring capacity, so that the chief difficulty is in securing a satisfactory standard for comparison. Condensers with solid dielectrics are unsatisfactory, since their capacity is a function of the frequency of charging and of the potential applied. This leaves the air condenser as the only satisfactory type of instrument that is suitable for a standard of capacity over wide ranges of potential and frequency.

The object of the present work is the construction and calibration of such a condenser, to be used by the department as a standard for the comparison of capacities.

II HISTORICAL

Early attempts were made to construct a standard condenser, whose capacity as determined by experiment would check with its calculated capacity. Among the first of these attempts was the work done by Faraday on spherical condensers, which he used in determining specific inductive capacities.

Later Lord Kelvin worked with the same type of condenser, but he found it difficult to check experimental results with those obtained by calculation. This was due to the difficulty in securing accurate spheres and also to the fact that it was difficult to support them in concentric relation. To overcome these objections Lord Kelvin constructed his guard ring condenser, which was the first really satisfactory standard condenser.

This condenser consisted essentially of an insulated brass disc 150 millimeters in diameter, surrounded by a guard ring and covered by a brass shield that was connected to the guard ring. Beneath and parallel to this disc was a larger one which was mounted on a screw by means of which the distance between the discs can be varied. In using the instrument the upper disc and guard ring are connected together and charged while the lower disc is connected to the earth. The guard ring is then disconnected from disc and discharged. The charge remaining on the disc can then be measured by the throw of a ballistic galvanometer.

Kelvin also invented a sliding cylindrical condenser, the essential parts of which are two brass cylinders of same diameter mounted on insulating base with their axes in the same straight line and their ends separated by a narrow gap. Within these two cylinders is a cylinder of smaller diameter with its axis concentric with the former two and supported on insulated supports so that the relative length enclosed by the two outer tubes can be varied. Various modifications of this form of condenser have been made giving it a wider

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1 Gray's Absol. Meas., Vol. 1, p. 419.

range of usefulness.

In 1892 Kelvin reported to the Royal Society[2] on a standard air condenser, or air leyden as he called it, which he had constructed. It consisted of two systems of parallel plates fastened together by four long metal bolts; each system being mutually insulated from the other. The outer plates of the first system were heavy metal discs while the remaining ones, together with those of the second system, were squares of thin brass sheets. The four bolts holding the plates of each system together pass through the corners of the squares and the distance between the plates is regulated by annular pieces of uniform length, which strip over the bolts. The two systems are built up together so that their plates alternate and their relative positions are such as to make the air gaps between them octagonal in shape. The apparatus is provided with clamps to hold it rigid for transportation, and also with a dust tight cylindrical metal case for protection. In the condenser there were twenty-two plates of the first system and twenty-three of the second, making in all forty-four octagonal air spaces, the average thickness of which was 0.301 cm. The approximate capacity of this condenser, which was used in measuring the capacity of short cables was 1.1×10^{-3} micro farads.

Dr. Alex Muirhead[3] has designed a form of standard air condenser consisting of a number of concentric brass tubes. Half of these tubes are carried by a conical brass casting, the outer surface of which contains steps upon which the tubes rest and by which they are

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2 Proc. Roy. Soc., Vol. 52, p. 6, 1892.

3 Br. Association Report on Elect. Standards, p. 373.

held in position. The other half are fastened by screws to a similar casting and suspended alternately between the tubes of the first group. The first casting rests on ebonite blocks which insulate it from the metal base. This base also carries a cylindrical case which covers the condenser and from the top of which is suspended the second conical block with its attached tubes.

In 1887[3] the committee on electrical standards appointed by the British Association recommended that the society construct a standard air condenser. Following out this idea a meeting of the committee was held in London at which Dr. Muirhead exhibited one of his condensers. The committee considered his condenser to possess unusual merits and decided to test it and two others that Mr. Muirhead offered to lend, before proceeding with the construction of any other form of condenser. These tests were carried out by the method of a vibrating commutator, due to Maxwell, and the results obtained were very satisfactory. Some later work on mica condensers emphasized the importance of having an air standard and the committee decided on Dr. Muirhead's form of condenser. Accordingly the Association had constructed by the Cambridge Scientific Company two condensers of capacity approximately .02 microfarad, which were kept in the testing room of the Cavendish Laboratory.

Tests were first made on the condensers for leakage. These tests, made by charging them to a certain potential, allowing them to stand for some time and then discharging, showed clearly that the humidity of the atmosphere affected very markedly the rate of leakage. In the better of the two condensers the leakage was as low as 0.1% per minute when the air was dried with sulphuric acid and

increased to 1% per minute when calcium chloride was used.

In determining the capacities a rotating commutator, devised by Professor Thomson and Mr. Searle, was used instead of Maxwell's vibrating commutator. The rotating commutator consisted of a split ring the two parts being mounted on a shaft. A water motor was employed for driving it and two wire springs made alternate contact on the segments of the commutator. The frequency of charging was determined by the stroboscopic method and the results show no variation in capacity for frequencies varying from thirty-two to eighty per second.

Later work has been done by Giebe[4], Zeleny[5], Hill[6], Curtis[7] and others on absorption effects, influence of temperature and pressure and of varying voltage used in charging. Giebe has found that for air condensers the absorption effect and the influence of change of voltage are not measurable, while the temperature and the pressure coefficients are readily determined. The absorption effect is very marked with mica condensers but it has been shown by Zeleny and Hill that this effect is always the same under the same conditions, so that the apparent capacity by any method of measurement is perfectly definite. Bedell[8] and Terry[9] have investigated temperature effects and determined the temperature coefficients. Curtis has shown that

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4 Zeit. für Instr., 29, p. 301, 1909.

5 Phys. Rev., 22, p. 65, 1906.

6 Phys. Rev., 26, p. 400, 1908.

7 Bureau of Standards, 6, p. 431, 1909-10.

8 Phys. Rev. 1, p. 81, 1893.

9 Phys. Rev., 21, p. 193, 1905.

voltage has an effect on the capacity in the case of silvered mica condensers.

III CONSTRUCTION OF CONDENSER

The object of the present work, as stated above, has been to construct and calibrate a condenser which could be kept in the department as a standard, and also to see how well its computed capacity would check with experimental results.

The plan of construction was to use plate glass, as it would offer fairly plane surfaces, and to cover it with some conducting material. Conductors of this type have been constructed before. C. Hockin[10] in 1879 reported to the British Association on measurements made in which a plate condenser constructed by Dr. Muirhead was used. The surfaces of this condenser were made conducting by depositing silver on them by the chemical process. In the present work smooth tin foil was secured from the Johnston Tin Foil and Metal Company of St. Louis, Missouri. This foil was twelve inches wide so that two strips covered one side of each plate, the latter being twenty-four inches square. In fastening the foil to the glass a very dilute solution of gelatin was used. This was poured on the glass and the foil rolled down with a small roller such as is used in mounting pictures on cardboard. The foil was allowed to project over the edges, thus putting the two sides in electrical contact. Twenty-one plates in all, were thus covered, the upper and the lower ones being covered on one side only. When assembled this gave twenty air spaces, thus forming twenty elementary condensers.

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10 Rep. Br. Assoc. for 1879, p. 285.

After the foil had dried in place a narrow strip was cut out leaving a square central portion, surrounded by portions which served as a guard ring. The narrow strip was not cut entirely around the central portion, but near one corner extended out to the edge of the plate, as shown in figure 1, thus leaving a tongue for conducting

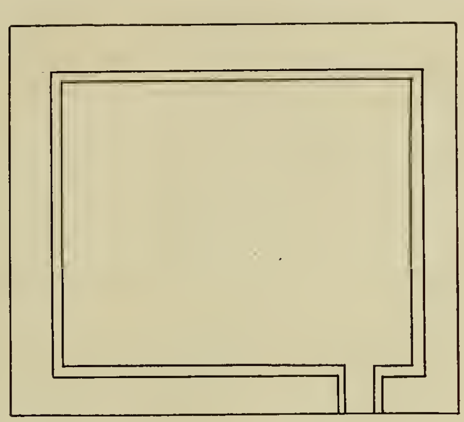

Fig. 1

the charge to the central portion. The other side of the plate is then cut in similar, the tongue coming out to the edge and joining with the one above, thus putting the two centres in electrical contact. Three of the plates, however, for reasons to be made clear later, were constructed with tops and bottoms independent. From these tongues contact was made to outside of condenser in a manner to be described later.

In cutting the foil as mentioned above, a square wooden form with tongue attached was placed on the plate in proper position and a tool with two cutting edges 2 mm. apart was then drawn along each edge. This made a gap 2 mm. wide, thus separating the central square from the guard ring.

These plates were placed in a tight wooden box built in the departmental shop for that purpose and separated from each other by

small blocks of glass placed eight on the guard ring and one in the center. These glass pieces were cut from photographic plates and their thickness determined with a micrometer. The glass varied so in thickness that it was difficult to secure enough blocks of the same thickness, so five different thicknesses varying from 0.2430 cm. to 0.2445 cm., were used. In placing the plates in the box pieces from the various groups were used alternately so that there were four sets of condensers each set containing five of the elementary condensers and of the same capacity. After the plates were properly placed in box tests were made with a magneto to see if they were properly insulated from each other and from the guard rings.

The plates were built up in the box with adjacent plates having their tongues on opposite sides of the box (See Fig. 2). Contact was made with these tongues by small brass clips that clamped the plates firmly and to each of which a copper wire was soldered. The three plates referred to above as not having their sides in electrical contact occupied positions between the different sections of the condenser, their tops being part of one condenser and their bottoms part of another. There were thus two sets of connecting wires from each of these plates. These wires were joined to brass strips mounted on two ebonite posts in the front of the condenser. There were four of these brass strips on each post and three wires connected to each strip. Each brass strip is connected to a binding post on outside of box by a long brass bolt which also serves to fasten the ebonite posts in position. The guard rings are connected in a similar manner and are entirely independent of the condenser proper. This arrangement of the condenser in four parts permits of each part being used independently of the others and of different

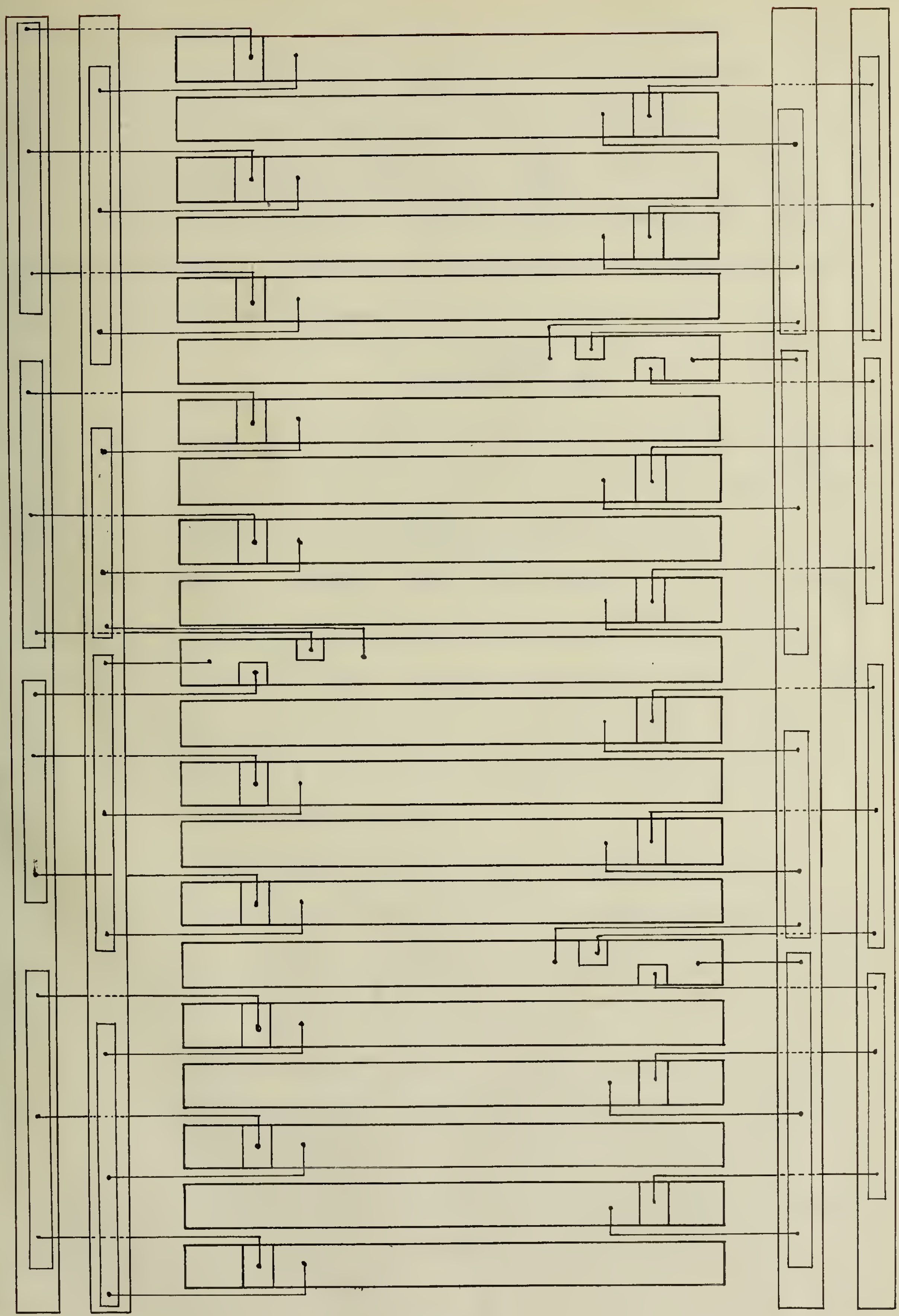

Fig. 2

parallel arrangements. Thus it was possible to determine the capacity of each part alone and then check results by various combinations.

The capacity of the condenser was calculated by the formula for parallel plate condensers, namely $C_1 = \frac{AK}{4\pi d}$, where A is the area of the air space, d the distance between plates, and C_1 the capacity in electrostatic units. Expressing the capacity in micro-farads the capacity for n plates becomes

$$C = \frac{(n-1)A}{4\pi d \times 9 \times 10^5}.$$

With the guard ring there is still a slight irregularity between it and the condenser. According to Lord Kelvin this is corrected for by adding to the area of the condenser one half of that of the slit, provided the latter is small. The inside square with the added correction was 55 cm. on each edge and the tongue had an area of 5 sq.cm. The five thicknesses of glass blocks were 0.2430, 0.2431, 0.2435, 0.2440, 0.2445 cm. From these data the calculated capacity of each condenser was .0054986 micro-farads, giving a total capacity for the condenser of .0219944 micro-farads.

IV MEASUREMENT OF CAPACITY - ABSOLUTE METHOD

To determine the capacity of the condenser experimentally two methods were used; Maxwell's absolute method and the bridge method of comparison using an A.C. galvanometer.

Maxwell's method is capable of a high degree of accuracy when there is no absorption effect. When the absorption is appreciable, however, the capacity depends on the number of charges and discharges per second: also on the actual time of contact of the charge and discharge brushes, even though the frequency remains constant. Being a null method variations in potential do not effect results, and it requires an accurate knowledge only of frequency of charging and

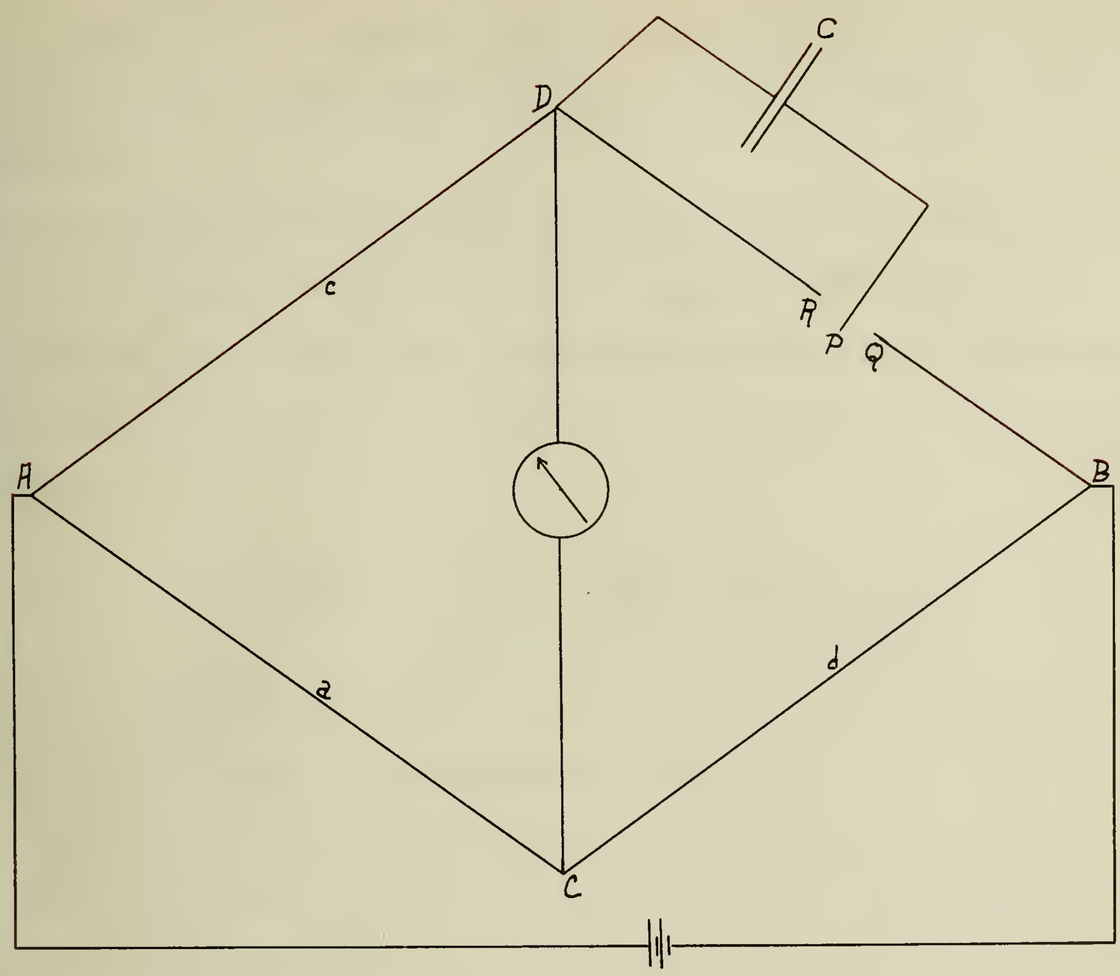

Fig. 3

resistances.

The capacity to be measured is placed in one arm of a Wheatstone bridge and the commutator or tuning fork P makes contact alternately with R and Q. When contact is made at Q the condenser is charged and on making contact at R it is discharged through the almost negligible resistance DR. When P is not touching R or Q the bridge arm DB is broken and a current flows from D to C through the galvanometer. On making contact at Q the condenser is charged by a current flowing partly through c and partly through a and the galvanometer. There is thus a current in opposite directions through the galvanometer as the condenser is charged and discharged. The bridge is balanced by

varying a and c until the currents in the opposite directions neutralize each other as is indicated by the zero deflection of the galvanometer.

The capacity is then given, according to J. J. Thomson, by the following formula in which n is the frequency of charging, a c and d the resistances of the three arms of the bridge as indicated in diagram, and b and g are the battery and galvanometer resistances respectively.

$$C = \frac{a}{ncd} \cdot \frac{1 - \dfrac{a^2}{(a+b+d)(a+c+g)}}{\left(1 + \dfrac{ab}{c(a+b+d)}\right)\left(1 + \dfrac{ag}{d(a+c+g)}\right)}$$

Ordinarily the first part of the formula gives very nearly the capacity of the condenser, the remainder constituting a correction factor. It is desirable to have the correction factor as near unity as possible, and to this end a should be small and c and d relatively large. With these conditions the values of b and g are not very important though it is better to have them small.

Methods of Charging Condensers.- Various methods at different times have been used for the rapid charge and discharge of condensers. Maxwell suggested the use of a tuning fork as a switch, the vibrating prongs carrying a stylus made and broke contact with a mercury cup. The objections to this method are the uncertainty of the period of contact and the fact that the contact may become poor by the loss of mercury from the cup due to the vibratory motion of the fork. J. J. Thomson[11] and R. T. Glazebrook[12] used a commutator driven by an electromagnet, the current through which was made and broken by a

11 Phil. Trans., 1883.

12 Phil. Mag., 1884.

vibrating tuning fork. A strip of brass carrying an iron piece vibrated between two contact points as the current was made and broken in the electromagnet. When touching one contact the condenser was charged and on reaching the other it was discharged. The points of contact were tipped with platinum to insure good electric connection.

Quite distinct from these vibration methods is the rotating commutator method. Such a method was used by Glazebrook in his work, referred to above, in measuring the Muirhead condenser of the British Association. Fleming and Clinton[13] have applied this method, using a commutator of their own design, and Rosa and Grover[14], in the Bureau of Standards made absolute measurements of capacity, using a commutator designed and constructed in the shops of the Bureau.

In the present work a commutator, constructed in the shop of the Physics Department, according to the design of Fleming and Clinton, was used. The instrument as constructed consisted of two independent commutators mounted on the same shaft, which in turn was supported by two small A shaped frames. Each commutator consisted of three brass discs or wheels, the inner one of which consists of eight radial pieces, while the outer two are like crown wheels having four teeth each. These three wheels are insulated from each other and so mounted that the teeth of one fall into the spaces between the teeth of the other, while the radial parts of the middle wheel occupy the spaces between the two sets of teeth. This complex surface is turned smooth and has the appearance showin in the sketch, (Fig. 4). Three brushes made of brass wire gauze and mounted on insulated holders

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13 Phil. Mag., May, 1903.

14 Bulletin of Bureau of Standards, Vol. 1, p. 153.

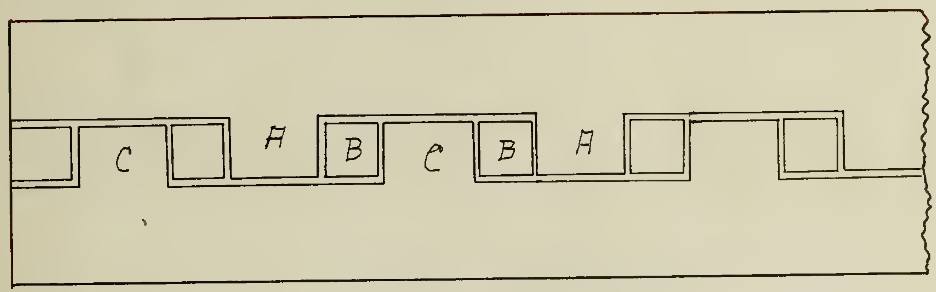


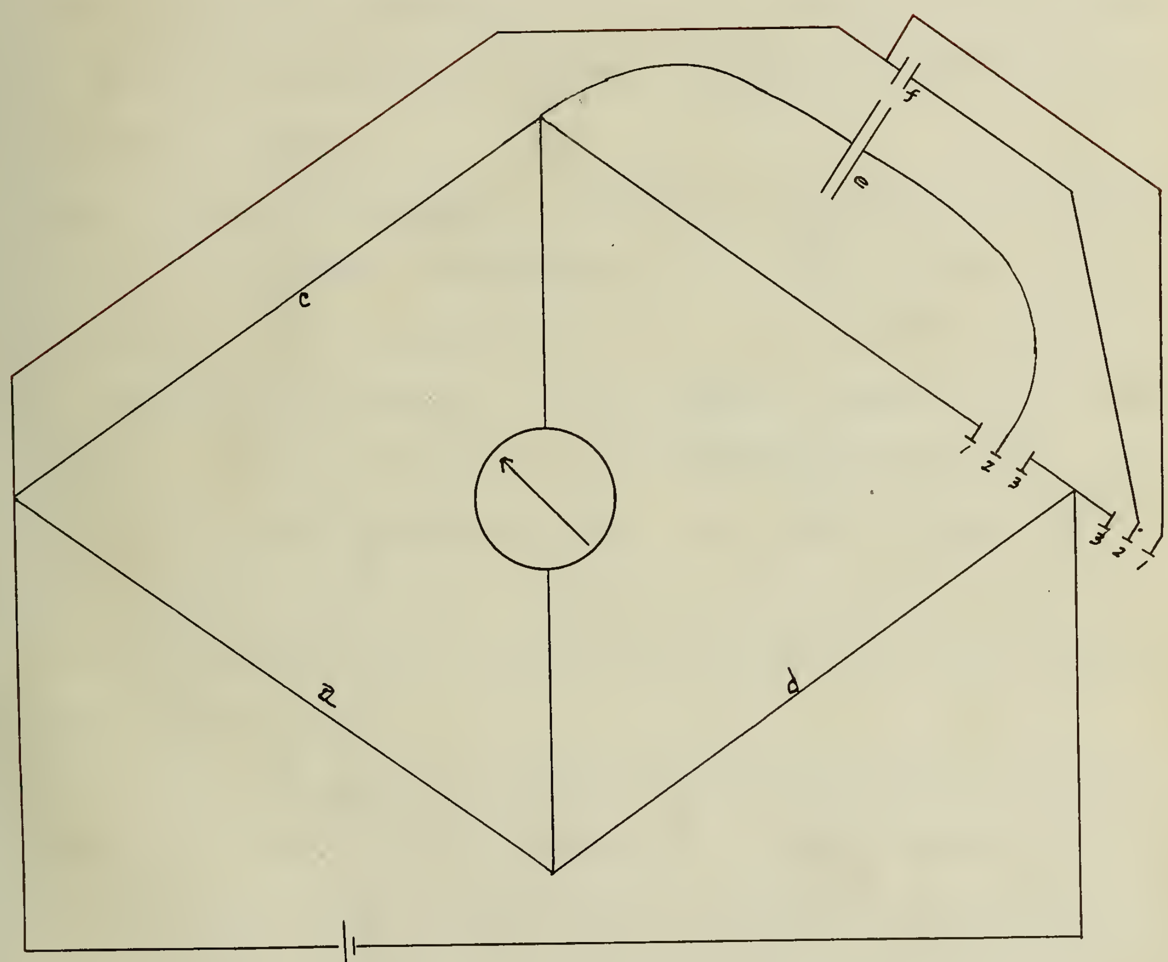
Fig. 4

press against the wheel,- one on each of the outer wheels while the middle one moves along the path A, B, C, being connected first with one of the outer brushes and then with the other. The pieces B serve to carry the brush smoothly from one contact to the other and prevent short circuiting the two outer brushes by insuring removal from A before contact occurs on C.

The revolutions were counted by a wheel driven by a worm gear on one end of the shaft. An electric circuit containing a sounder was closed on each revolution of the wheel by contact of a metal peg in the wheel with a brass spring. Each rotation of the wheel corresponded to one hundred of the commutator and thus 400 charges and discharges of the condenser.

The commutator was driven by a quarter horse power D.C. shunt wound motor mounted on the same base with itself. The connection was made with a leather belt instead of the flexible coupling as used by Fleming and Clinton, and also in the Bureau of Standards. The current for the motor was furnished by fifty-five storage cells.

The arrangement of apparatus as actually used is sketched in Fig. 5. a, c and d are resistances forming three arms of the bridge



e = the air condenser

f = the guard ring

Fig. 5

while the condenser and commutator form the fourth one. The second part of the commutator, connected as shown in diagram, is used to charge and discharge the guard rings. The resistance d was part of a megohm box built by Siemens and Halske, the other resistances were Otto Wolff boxes. The galvanometer was a D'Arsonval type H, constructed by Leeds and Northrup, having a resistance of 243 ohms. The battery used in charging the condenser consisted of five storage cells joined in series.

Measurement of Frequency.- As already stated the period of 400 charges of the condenser corresponds to the time between two strokes of the sounder. The frequency was at first determined by taking the time of ten such periods with a stop watch as suggested by Fleming and Clinton. But this method was not sufficiently accurate, so it was discarded and a chronograph used. This gave a high degree of accuracy, the only objection being the extra work in reading the period from the chronograph record, which had to be done for each independent determination.

Not having any means of control it was necessary to depend on the constancy of the motor. An observer at the galvanometer could readily note any change in the frequency by the galvanometer deflection. When the galvanometer was steady the chronograph was started and time and strokes of sounder recorded. During the run the galvanometer would not remain entirely steady. In case the variations were too great the determination was discarded and a new trial made.

This was, of course, not an entirely satisfactory method as it involved waiting for steady conditions. Some means of controlling the speed of the motor, as the carbon resistance used by the Bureau of Standards or the centrifugal governor used by Giebe, would have

been highly advantageous. Likely some of the difficulty experienced was also due to the use of a belt for driving the commutator. Direct connection of motor and commutator by means of a flexible coupling would have eliminated this difficulty.

V MEASUREMENT OF CAPACITY - COMPARISON METHOD

The comparisons of capacities in the present work were made by the familiar method of DeSauty. This method is similar to the Wheatstone bridge method of measuring resistances. Resistances R_1 and R_2 are placed in two adjacent arms of the bridge, while a standard capacity C_2 and the one whose value is to be determined, C_1, occupy

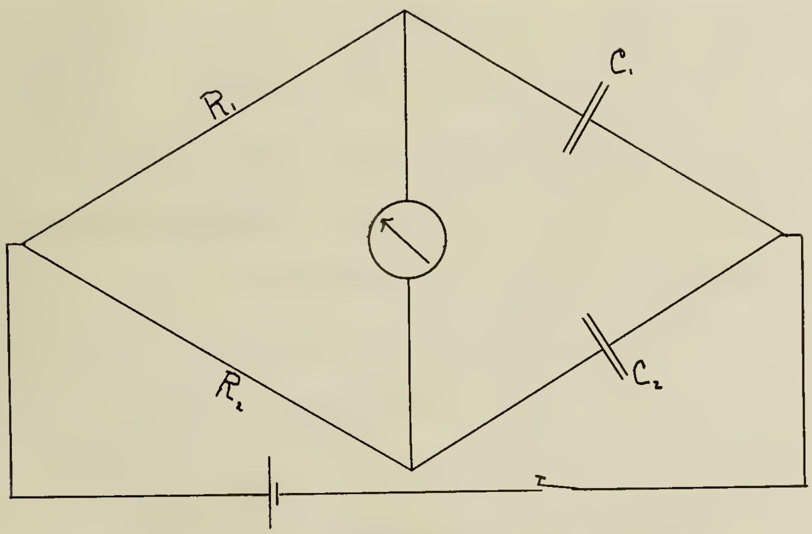


Fig. 6

the other two arms. The battery and galvanometer are connected in the manner shown in the diagram (Fig. 6). Adjustment is made by varying the resistances until there is no deflection on opening or closing the switch. When these conditions are set up the potentials at the two terminals of the galvanometer are always equal and the relation $C_1 = C_2\frac{R_2}{R_1}$, holds. A complete discussion of the theory of the method is given in the Philosophical Magazine[15] by R. T. Glazebrook.

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15 Phil. Mag., May 1881, p. 370.

The method is applicable only to condensers that have no absorption coefficient.

In the present work an A.C. galvanometer built in the shop of the department was used for determining the balance point. The moveable coil of the instrument, consisting of 600 turns of a No. 40 copper wire, was suspended in the field of a C-shaped electromagnet. The magnet consists of 600 turns of No. 16 copper wire, wound on a laminated core built of sheets of transformer iron. The galvanometer was controlled by the method due to Terry, namely, shunting a resistance and a capacity across it. A maximum sensibility was secured by varying the resistance or the capacity to produce a lag or a lead as conditions required. In case there was large capacity in the bridge, the capacity in the shunt was decreased thus producing lag and if the bridge capacity was small an increase in the control capacity produced the desired lead. The sensitiveness of the instrument varied with the bridge capacity, but with capacities of the magnitude used it was possible to detect readily 0.1 ohm in three or four thousand. In previous work done by Mr. J. P. Coyle with the same instrument a sensibility of 0.2 ohm in 20,000 was reported with capacities of the magnitude of .024 micro-farad. As this is far beyond the accuracy of the resistance boxes, no attempt was made to secure this degree of sensibility.

The current for the present work was supplied by a motor-generator set. The direct current motor of the set was driven by a current from fifty-five storage cells, as the dynamo current was early found to be too unsteady. The generator furnished a current with a potential of 110 volts and a frequency of about 60 cycles.

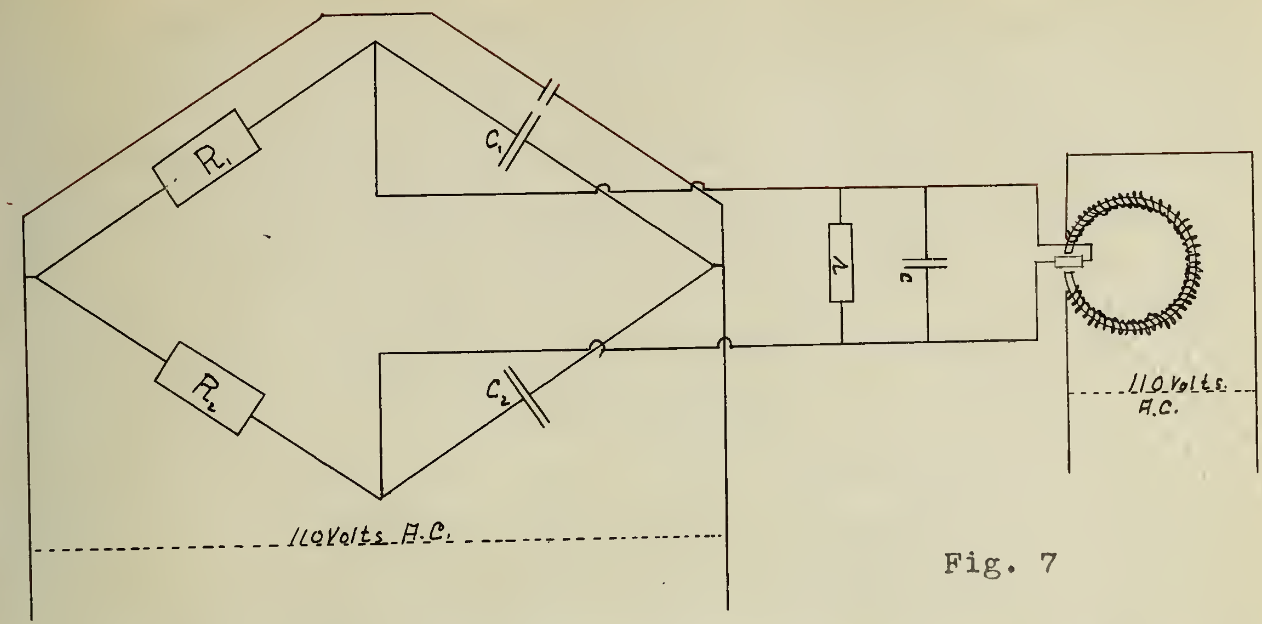

Fig. 7

The set up of apparatus as used is sketched in Fig. 7, the battery being replaced by the generator as a source of current. The field of the galvanometer is excited by the same source so as to be in phase with current through the bridge. The guard ring is also joined across the outside of bridge as in the absolute method.

VI DATA AND RESULTS

In the following discussion of data the four parts of the condenser are referred to as C_1, C_2, C_3 and C_4, numbering from the top to the bottom of the series.

It was the intention to determine the capacity of each of these condensers and of various combinations of the same by the absolute method. However, owing to the inability to obtain a constant frequency it was found that the capacities could be determined more readily as well as more accurately by the comparison method. Since in this method a standard is necessary, a careful determination of one of the capacities, C_4, was made by the absolute method and the values of the other capacities determined by comparison with this.

The results of the absolute determination of C_4 are given in

Table I. While the individual determinations have a maximum difference of .04 per cent, the mean is well within the range of error in the resistance used, since they were not especially calibrated for the work and had a possible error of from .04 to .06 per cent.

TABLE I

Capacity of C_4 by Absolute Method

d = 300,000 ohms

No.	A	C	N	C_4 in m.f.
1	198.9	1500	74.511	.0059320
2	200.2	1510	74.498	.0059323
3	201.6	1520	74.520	.0059327
4	202.8	1530	74.463	.0059336
5	203.9	1540	74.361	.0059344
6	205.2	1550	74.374	.0059334
7	209.2	1580	74.385	.0059333
			Mean =	.0059331

TABLE II

Comparison of C_1 with C_4

C_4 = .0059331 m.f.

No.	R_2	R_1	C_1 in m.f.
1	2800	2831.7	.0058667
2	2850	2882.2	.0058668
3	2870	2902.3	.0058671
4	2900	2932.8	.0058667
5	2920	2953.0	.0058666
6	2835	2968.1	.0058669
7	2955	2988.4	.0058668
8	2965	2998.5	.0058668
		Mean =	.0058668

TABLE III

Comparison of C_2 with C_4

C_4 = .0059331 m.f.

No.	R_2	R_1	C_2 in m.f.
1	2700	2738.3	.0058501
2	2750	2789.1	.0058499
3	2825	2865.0	.0058503
4	2850	2890.5	.0058500
5	2875	2915.8	.0058501
6	2900	2941.2	.0058500
7	2925	2966.5	.0058501
8	2950	2991.8	.0058502
		Mean =	.0058501

TABLE IV

Comparison of C_3 with C_4

$C_4 = .0059331$

No.	R_2	R_1	C_3 in m.f.
1	2825	2809.5	.0059658
2	2850	2834.3	.0059660
3	2875	2859.2	.0059659
4	2900	2884.0	.0059660
5	2925	2908.9	.0059659
6	2950	2933.7	.0059661
7	2975	2958.5	.0059662
8	2990	2973.5	.0059660
		Mean	.0059660

TABLE V

Comparison of C_1 and C_2 in Parallel with C_4

$C_4 = .0059331$ m.f.

No.	R_2	R_1	$C_{1\&2}$ in m.f.
1	4840	2456.8	.0116885
2	4870	2472.0	.0116886
3	4895	2484.7	.0116885
4	4920	2497.4	.0116885
5	4940	2507.5	.0116887
6	4965	2520.2	.0116887
7	4985	2530.2	.0116894
8	4998	2536.9	.0116889
		Mean	.0116887

TABLE VI

Comparison of C_1 and C_3 in Parallel with C_4

$C_4 = .0059331$

No.	R_2	R_1	$C_{1\&3}$ in m.f.
1	4800	2407.4	.0118297
2	4825	2420.1	.0118289
3	4850	2432.6	.0118291
4	4875	2445.1	.0118293
5	4900	2457.6	.0118295
6	4925	2470.2	.0118292
7	4950	2482.6	.0118299
8	4975	2495.2	.0118296
		Mean	.0118294

TABLE VII

Comparison of C_2 and C_3 in Parallel with C_4

$C_4 = .0059331$ m.f.

No.	R_2	R_1	$C_{2\&3}$ in m.f.
1	4800	2417.6	.0117798
2	4840	2437.7	.0117800
3	4850	2442.7	.0117802
4	4880	2457.8	.0117803
5	4900	2467.9	.0117801
6	4930	2483.2	.0117793
7	4960	2498.3	.0117793
8	4990	2513.4	.0117793
		Mean	.0117798

TABLE VIII

Comparison of C_1, C_2 & C_3 in Parallel with C_4

C_4 = .0059331

No.	R_2	R_1	$C_{1,2,3}$
1	8750	2940.3	.0176562
2	8800	2957.3	.0176550
3	8825	2965.7	.0176551
4	8860	2977.4	.0176560
5	8875	2982.3	.0176563
7	8900	2990.8	.0176557
8	8925	2999.2	.0176557
6	8890	2987.4	.0176559
		Mean	.0176557

TABLE IX

Comparison of C_3 and C_4 in Parallel with C_1

C_1 = .0058668 m.f.

No.	R_2	R_1	$C_{3\&4}$ in m.f.
1	4050.4	2000	.0118814
2	4151.5	2050	.0118810
3	4252.9	2100	.0118814
4	4354.0	2150	.0118810
5	4455.4	2200	.0118813
6	4556.3	2250	.0118804
7	4657.9	2300	.0118813
8	4758.9	2350	.0118806
		Mean	.01188105

TABLE X

Comparison of C_2, C_3 & C_4 in Parallel with C_1

C_1 = .0058668 m.f.

No.	R_2	R_1	$C_{2,3,4}$ in mf.
1	9250	3061.2	.0177277
2	9300	3077.9	.0177268
3	9350	3094.2	.0177282
4	9400	3110.9	.0177273
5	9500	3143.8	.0177284
6	9600	3177.1	.0177272
7	9700	3210.0	.0177284
		Mean	.0177277

TABLE XI

	Caps. in m.f. by comp. with C_4	Caps. in m.f. by addition of parts	% of difference
C_1	.0058668		
C_2	.0058501		
C_3	.0059660		
$C_{1\&2}$	.0116887	.0117169	0.24
$C_{1\&3}$	.0118294	.0118328	0.029
$C_{2\&3}$	.0117798	.0118161	0.308
$C_{1,2,3}$	.0176557	.0176829	0.148
	By comp. With C_1		
$C_{3\&4}$	.0118810	.0118991	0.15
$C_{2,3,4}$	.0177277	.017749	0.12

Tables II to VIII give the results obtained by comparing C_4 with C_1, C_2, C_3 and all possible parallel combinations of the same. Tables IX and X were obtained in a similar manner, using C_1 as a standard with the capacity given for it in Table II. The maximum difference in any set of readings varies from .006 to .01 per cent, which is approximately one sixth as great as the variation in the absolute determination.

In Table XI is given a condensed summary of the results of the previous tables. Column two gives the experimental values for the individual condensers and the various combinations, while in column three are the values of the combinations obtained by adding the values of the individual capacities. The per cents of difference are given in column four. The greatest differences occur in the results for $C_{1\&2}$ and $C_{2\&3}$, being approximately 0.3%. This suggests some possible defect in construction of C_2, since $C_{1\&3}$ gives very satisfactory results. In case of $C_{1,2,3}$, C_2 forms a smaller part of the total capacity measured and the per cent of error is accordingly lessened.

The fact that the experimental results for parallel connections are lower throughout than the sums may be due to induction effects. In the case of a single condenser the area exposed to induction effects is greater in proportion to the capacity than with a number joined in parallel. This explanation is apparently strengthened by the fact that in determining the capacities it was observed that if a person placed his hands on the condenser box during a determination the capacity was changed. In one instance this change was observed to amount to 0.2 per cent of the capacity being measured. These induction effects might be prevented by properly shielding the condenser with a metallic covering.

In this same connection, might also be mentioned the fact that when two, not adjacent, condensers as C_1 and C_3 were joined in parallel it was necessary to cross the connections in such manner as to make the sides of the condensers next to the intervening capacity of the same potential. Otherwise the capacity was greatly increased. In one set of data taken without observing this arrangement, the effect amounted to almost ten per cent of the true capacity.

From the above data it is evident that the capacity of the four condensers in parallel is not the sum of the individual capacities. To determine experimentally this value necessitated using some standard outside the air condenser itself. For this purpose a Leeds and Northrup mica condenser was calibrated against C_4 and used as a standard. According to Zeleny, Hill and others this apparent capacity is always a perfectly definite quantity provided the conditions under which it is used are constant. The apparent capacity as given in Table XII is .020707 m.f. Using this value the capacity of the air condenser was determined, the results being given in Table XIII.

A very interesting result of the present investigation is brought out by a comparison of the experimental value of the capacity of the air condenser, as given in Table XIII, with the theoretical value as determined by the formula given on page 9. The latter value, .021994 micro-farads, is 7 per cent lower than the experimental results. Several possible factors may enter into the production of this wide discrepancy between theory and experiment. Probably the most important of these is the possibility that the thickness of the air spaces was less than the values used in the calculation. This would be due to the weight of the plates slightly imbedding the small glass blocks in the tin foil. The plates, too, were not uniformly plane, as was

TABLE XII

Capacity of Mica Condenser by Comparison with C_4

C_4 = .0059331 m.f.

No.	R_2	R_1	C_{mica} in m.f.
1	6980.4	2000	.020708
2	7329.2	2100	.020707
3	7678.3	2200	.020707
4	7852.8	2250	.020707
5	8027.3	2300	.020707
6	8201.7	2350	.020707
7	8376.2	2400	.020707
8	8551.0	2450	.020708
		Mean	.020707

TABLE XIII

Capacity of Air Condenser by Comparison with Mica Condenser

No.	R_2	R_1	$\frac{R_2}{R_1}$	C_{air} in m.f.
1	3500	3079.6	1.13651	.023534
2	3600	3167.7	1.13647	.023533
3	3700	3255.7	1.13647	.023533
4	3800	3343.6	1.13650	.023534
5	3900	3431.6	1.13650	.023534
6	4000	3519.6	1.13649	.023533
7	4100	3607.6	1.13649	.023533
8	4200	3695.6	1.13649	.023533
			Mean	.023533

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